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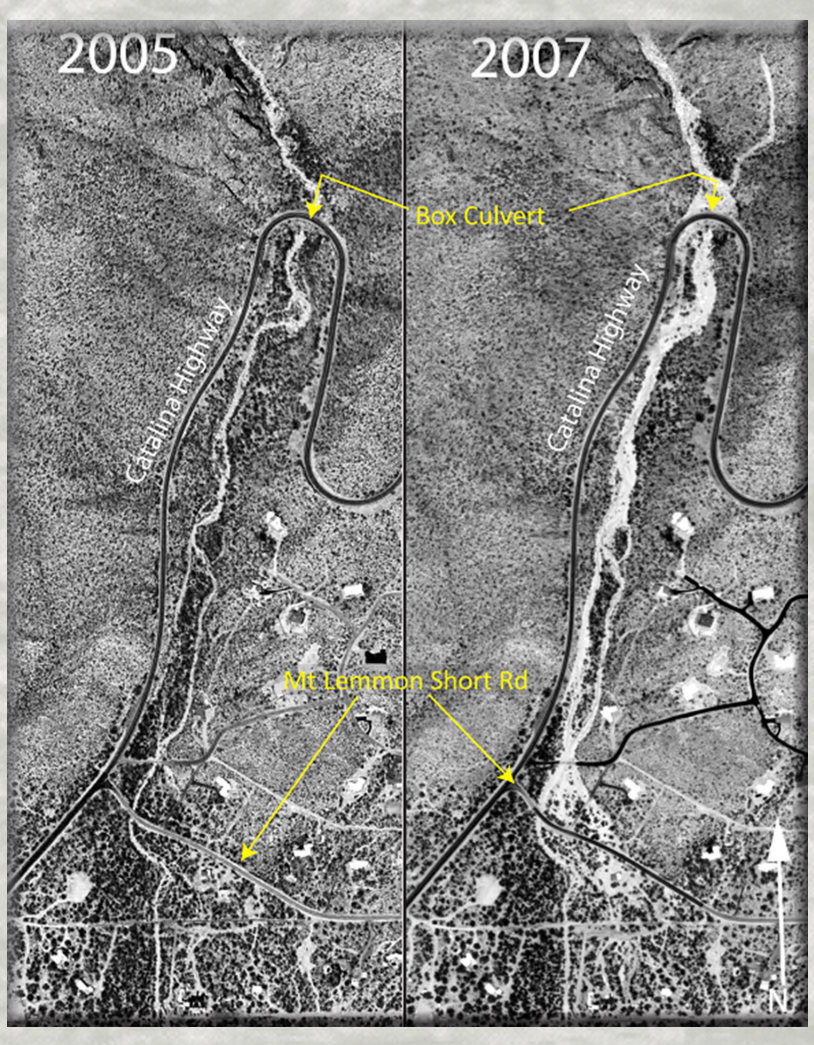

Methods for Evaluating Alluvial Fan Flood Hazards From Debris Flows in Maricopa County, Arizona

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December 2010

ARIZONA GEOLOGICAL SURVEY

Executive Summary

This study evaluated methods to quantify the risk of debris-flow initiation and runout potential to impact alluvial fan flooding hazards in Maricopa County. Debris flows are unsteady, non-uniform, very poorly sorted sediment slurries that are generated when hillslope soils become saturated and fail. While there is some evidence that debris flows have occurred in Maricopa County on very steep slopes of mountainous watersheds, there are no documented cases of historic debris flows impacting flood hazards on mid-piedmont alluvial fans. Based on known general characteristics of debris-flow behavior, as well as on the specific climatic and geologic conditions in Maricopa County, the expected recurrence interval for debris flows in Maricopa County probably exceeds 1,000 years. Furthermore, because of the regional physiography and watershed characteristics, it is likely that future debris flows will have low volumes because of limited sediment supplies, will travel only short distances from their point of initiation due to their coarse sediment composition and low clay content, and that most will not reach the active areas of alluvial fans, particularly the fans that are located away from the mountain front.

To assess potential debris flow impacts on alluvial fan flooding, a combined approach of geologic reconnaissance and mapping, with a two-phase application of the LAHARZ debris-flow runout hazard model is recommended. Geologic reconnaissance will confirm the presence or absence of relatively young debris-flow deposits, and provide details of the basin and piedmont conditions which will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. Debris-flow runout models will provide hazard information regarding potential travel distances, and the volumes required to reach those distances.

Acknowledgment:

This report was prepared by the Arizona Geological Survey on behalf of JE Fuller/Hydrology & Geomorphology, Inc. It was prepared for the Flood Control District of Maricopa County (FCDMC) under Contract #FCD2008C007, Work Assignment #1, Task 2.7. This open-fire report was included as Appendix H in the full report submitted to FCDMC entitled "Refinement of Methodology: Alluvial Fan Flood Hazard Identification".

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Introduction

Debris flows are significant geologic hazards worldwide (Larsen, 2008). Historical occurrences (<150 years) of debris flows have been documented in all three physiographic provinces in Arizona (Figure 1), including the Grand Canyon, isolated peaks on the Colorado Plateau (Melis and others, 1995; Griffiths and others, 1996; Webb and others, 2008a), the Mogollon Rim, the Mazatzal Mountains in the Transition Zone (Pearthree and Youberg, 2004; Jenkins, 2007; Youberg, 2008), and numerous mountain ranges within the Basin and Range Province of central and southern Arizona (Wohl and Pearthree, 1991; Webb and others, 2008b; Youberg and others, 2008). Pleistocene and Holocene debris-flow deposits provide ample geologic evidence of debris-flow activity in most of Arizona's mountain ranges. Extensive, large caliber debris-flow deposits on alluvial fans across central and southern Arizona record periods of aggradation during the wetter climates of the Pleistocene and early Holocene (older than about 8,000 years), and attest to the primary importance of debris flows in constructing fans during that time. Geologic mapping of debris-flow deposits on fans along the front range of the Santa Catalina Mountains show that mid-Holocene to modern debris-flow deposits are smaller and more limited in extent than Pleistocene to early Holocene deposits (Youberg and others, 2008).

The objective of this debris flow assessment is to determine and quantify how debris flow potential influences alluvial fan flood hazards in Maricopa County. The purpose of this report is to evaluate methodologies to assess the potential for debris flows to impact alluvial fan flooding in Maricopa County. The report evaluates and recommends methods for determining potential debris flow occurrence and run-out onto the alluvial fan flood hazard areas. Other debris-flow hazard issues such as expected magnitude, frequency, or direct impacts on developments located at the base of steep slopes (Péwé, 1978) are not directly addressed in this report.

Debris Flows – Definitions, Descriptions & Rheology[1]

Definition

Debris flows are unsteady, non-uniform, very poorly sorted sediment slurries (Costa and Williams, 1984; Iverson, 2003) that are generated when hillslope soils become saturated and fail. As pore pressures in saturated soils increase and shear strengths decrease, a critical point of failure occurs resulting in a rapidly mobilized soil mass that transforms into a viscous slurry through liquefaction or dilatancy (Costa, 1984; Iverson and others, 1997).

Descriptions

A review of debris-flow literature reveals considerable variability and contradictory usage of descriptive terms due to the inconsistent appearance of debris-flows. In general, flood flows are classified as water floods, hyperconcentrated flows, and debris flows based on sediment concentration and flow rheology (Pierson and Costa, 1987; Pierson, 2005). Debris flows are sediment-rich slurries at one end of a continuum with floods (water flows) at the other end, and hyperconcentrated flows in the middle. Flood flows typically contain less than 40% sediment by volume and are turbulent Newtonian flows (Pierson and Costa, 1987). Clay, silt and sometimes sand are transported as suspended sediment in floods while gravel is generally transported as bedload. Hyperconcentrated flows have around 40-60% sediment by

[1] Rheology. The study of the flow, behavior and deformation of materials.

volume and have sufficient interaction between grains to keep sediment in suspension as long as flow velocities are maintained (Pierson, 2005). Thus deposits from both flood and hyperconcentrated flows exhibit some degree of sorting by grain size (Pierson, 2005).

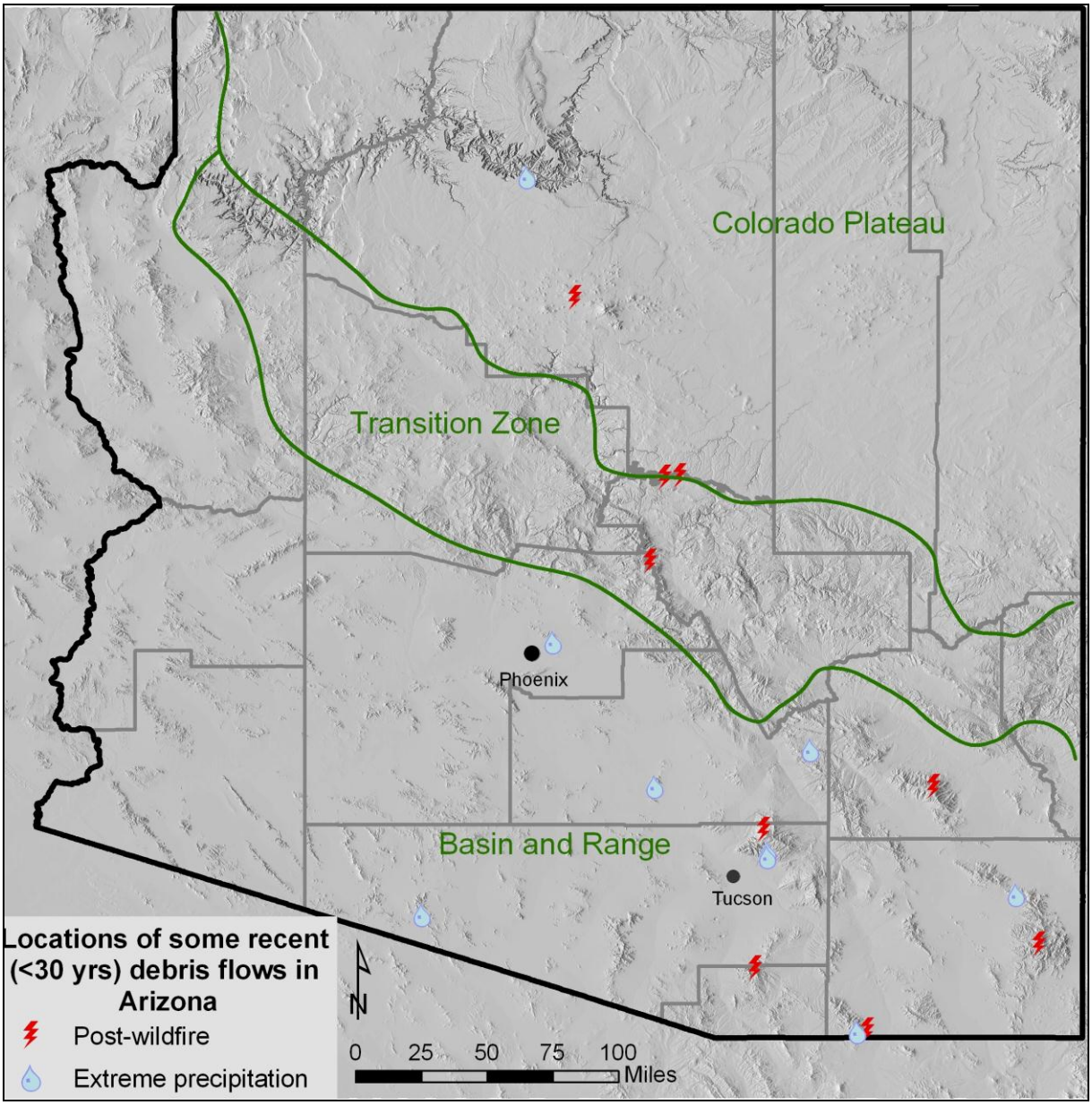

Figure 1. State of Arizona with the three geophysical provinces (green), and locations of some known recent (<30 yrs) debris flows. Red symbols indicate those debris flows that were fire-related. Blue symbols are those that occurred due to extreme precipitation.

Debris flows differ from flood flows and hyperconcentrated flows both in the amount of sediment they contain, more than 60% by volume (Pierson and Costa, 1987), and in flow behavior. Debris flows are grain-fluid mixtures that have unsteady flow characteristics due to fluctuating states between the fluid and solid phases. The fluid matrix phase of a debris flow is composed of clay, silt, and sand in suspension and is driven by high pore pressure. The solid-particle phase is composed of coarse clasts that interact by

frictional and gravitational forces. The solid and fluid phases maintain flow by transferring momentum both within and between each phase simultaneously (Iverson, 1997). This interaction within and between phases is what distinguishes debris flows from other flows and prevents particles from settling, even at low velocities, resulting in deposits that exhibit minimal sorting (Iverson and Vallance, 2001; Pierson, 2005).

Rheology

Debris-flow behavior varies depending on grain size and the dominance of the solid and fluid phases. Behavior in a single debris flow can transform from a viscous plug to a very fluid flow through time and space as composition, pore pressures and grain-to-grain interactions evolve (Iverson, 2003). Fluid-flows are dominated by the matrix phase, and are typically composed of fine-grained clay, silt and sand, or ash if volcanic related. Fluid flows behave as a single-phase flow exhibiting Bingham-type flow behavior (Parsons and others, 2001), and tend to have thinner deposits and longer runout distances (Iverson, 2003). Granular-flows have a wider range of material sizes and behave more as a two-phased, non-Newtonian flow with a fluid matrix and a solid-particle phase (Iverson, 1997; Iverson, 2003). These flows can have very little silt and clay in the matrix resulting in shorter runout distances and thicker deposits (Iverson, 2003). Recent debris flows in the Santa Catalina Mountains near Tucson appeared to be granular-flows based on the presence of abundant coarse clasts in their deposits and lack of clay in the matrix (Webb and others, 2008b). Coarse deposits from other historical debris flows in Arizona (Péwé, 1978; Wohl and Pearthree, 1991; Webb and others, 2000) were also most likely deposited by granular flows. In Maricopa County, debris flows are expected to be granular, with coarse clasts and low clay content, resulting in shorter runout distances.

There are three distinct zones in which different debris-flow processes occur - initiation, transportation and deposition (Hungr, 2005). Initiation zones are located on steep upper hillslopes and are most often identified by distinct head scarps of slope failures where debris flows are generated (Figures 2 and 3). Generally, the term landslide-induced debris flow is used to describe a shallow translational failure of thin soil over an impervious surface, such as bedrock, that liquefies and transforms into a debris flow (Iverson and others, 1997; Santi and others, 2008). Debris flows can also be initiated in channels when channel bed sediments are mobilized by runoff (Costa, 1984). Although the initiation mechanisms are not well understood, runoff-induced debris flows typically occur after wildfire when relatively high-frequency storm events can generate very high runoff volumes due to the removal of vegetation and other fire-induced changes (Wohl and Pearthree, 1991; Cannon, 2001; Moody and Martin, 2001; Moody and others, 2008; Santi and others, 2008). Changes due to wildfire include decreased interception and surface roughness due to consumption of plant and duff material, decreased infiltration due to surface sealing and fire-induced water repellency, which leads to increased runoff and flow velocities. Probable initiation mechanisms for runoff-induced debris flows include channel bank collapse, channel bed failures, or the temporary emplacement and failure of dams.

Once initiated, debris flows travel downslope via existing channels through the transportation zone (Figures 2 and 3), changing character in time and space. Debris flows commonly move in surges led by a coarse-boulder front (head), followed by a liquefied slurry (body), and a more watery tail, which is commonly a hyperconcentrated flow (Hungr, 2005). As debris flows move downslope, longitudinal sorting of coarse clasts results in the deposition of lateral levees , either in the transportation or deposition zones, which act to confine the flow (Figure 4) (Hungr, 2005). Although levees may be deposited along the channel in the transportation zone, they are most obvious in areas with less lateral topographic

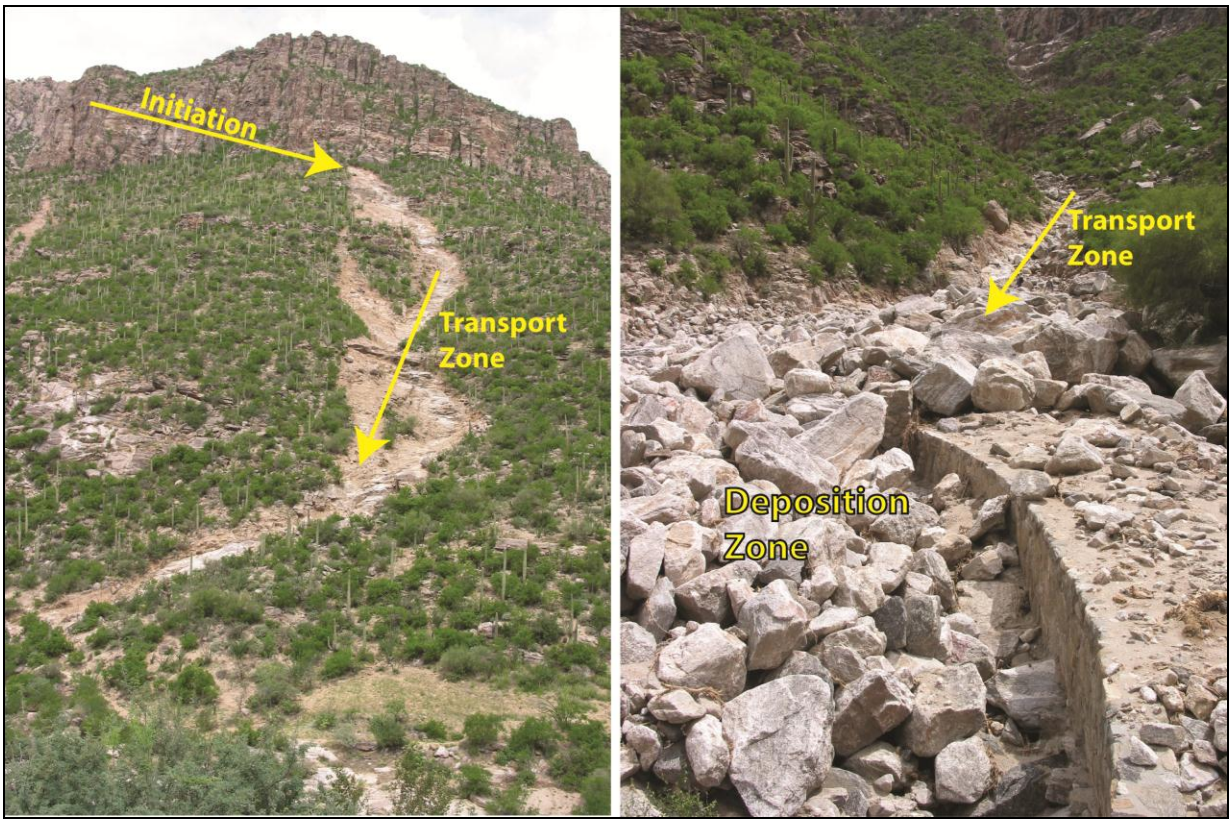

Figure 2. Examples of initiation, transport and deposition zones from Sabino Canyon, Santa Catalina Mountains, Tucson (modified from Youberg and others, 2008). These debris flows are on very steep slopes in the watershed above the alluvial fan apex.

Figure 3. Example of a landslide scarp at the top of an initiation zone (left) and transportation zone in a debris-flow channel (right). Blue arrows indicate flow direction.

confinement. Debris-flow volumes can change significantly during downslope movement as scouring or deposition occurs (Iverson and Vallance, 2001). Debris-flow deposition occurs in areas where lateral

confinement decreases and/or channel slope decreases.[2] Depositional areas are often alluvial fans located at the mouths of drainages (Figure 4).

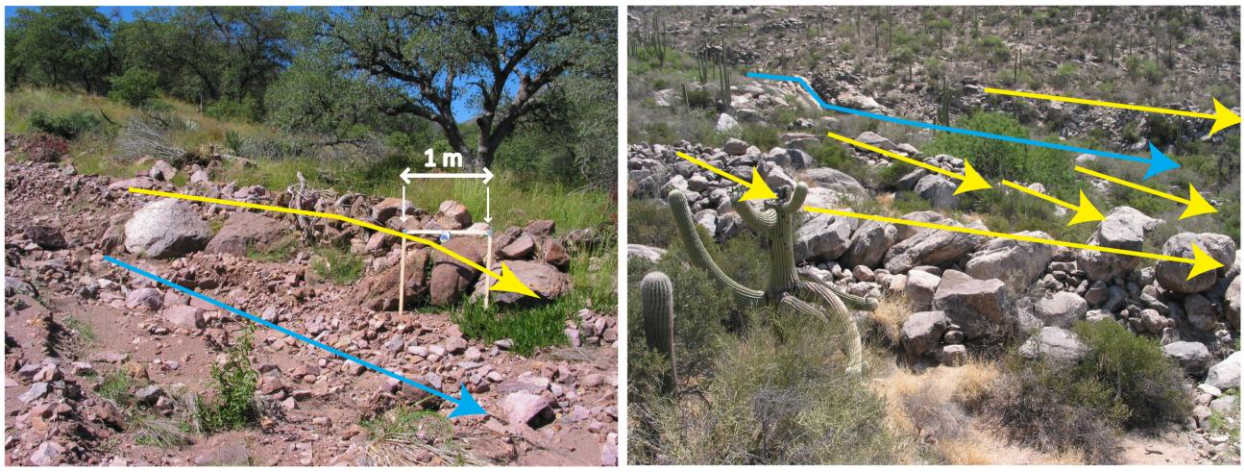

Figure 4. Examples of debris-flow levees (yellow arrows). Recent (2006) debris-flow levee along a channel in the Huachuca Mountains (left photo) and late Pleistocene debris-flow levees near the apex of an alluvial fan in the Santa Catalina Mountains (right photo). Blue arrows indicate channel flow direction.

Factors That Affect Debris Flow Initiation, Transport and Deposition

Numerous factors influence the initiation, transportation and deposition of debris flows. Initiation occurs when hillslope soils become saturated, pore pressures increase and shear strengths decrease to the critical point of failure (Costa, 1984; Iverson and others, 1997). Some factors that increase the likelihood of initiation include steeper slopes, exposed bedrock, which increases runoff and flow velocity, high antecedent moisture conditions, and prolonged or intense rainfall (Giraud, 2005).Disturbances such as wildfires decrease vegetation cover resulting in decreased interception, and infiltration, and increase runoff, increasing the likelihood of initiation. In areas where trees are killed by fires, root strength also decreases with time leading to an increase in the likelihood of slope failure (Gerber and Roering, 2003).

Basin relief and channel gradient influence debris-flow transportation and deposition, but the most important factors are debris-flow volume and composition. Debris-flow composition determines the behavior of the flow. Finer-grained, fluid flows travel farther and have thinner deposits, while coarser-grained granular flows do not travel as far and have thicker deposits (Iverson, 2003). Debris-flow volume is determined both by the magnitude of the hydroclimatic event and by the amount of sediment available for transport. In supply-limited basins, such as those in Maricopa County, sediment is stored over time as loose colluvium on hillslopes, in colluvial wedges at the base of hillslopes, and in channels (Jakob, 2005). With an appropriate triggering rainfall, sediment is released through hillslope failures, colluvial wedge and channel bank collapses, and channel bed failures and/or scouring (Giraud, 2005; Jakob, 2005). The amount and nature of material released from storage will be a key factor in debris-flow runout.

[2] While there are some reported slope thresholds for deposition, they vary by environment and do not appear to be consistent. There are no known reported thresholds for Arizona.

Historical Debris Flows in Arizona

Historical records from relatively populous areas during the past 150 years reveal some debris flows in the mountains surrounding Tucson (Webb and others, 2008b), and small but damaging debris flows in Phoenix area during the 1970's (Péwé, 1978). Documented historical debris flows, however, are typically limited to steep watersheds in mountainous terrain and sparsely populated areas. Over the past 30 years, Arizona saw an increase in fire-related debris flows as the size and severity of wildfires increased (Wohl and Pearthree, 1991; Pearthree and Youberg, 2004; Schaffner and Reed, 2005). Numerous debris flows have also been generated from low-frequency, high-magnitude storms, such as dissipating tropical storms (Griffiths and others, 1996; Webb and others, 2008b) as shown in Figure 1. No evidence or records of any documented historical debris flows in Maricopa County exiting mountain fronts or flowing onto active alluvial fans was identified during the course of this study.

While the record of historical debris-flow deposits demonstrates that debris flows can occur in Arizona, the frequency of debris flows in this desert region may be an order of magnitude less than in humid areas (Webb and others, 2008b). The occurrence of debris flows are a culmination of several factors, including a triggering hydroclimatic event, a watershed with sufficient material available for entrainment, and slopes steep enough to initiate and maintain flow movement. Debris flows are less frequent in supply-limited basins, such as those found in Arizona, where coarse material accumulates in channels over relatively long time periods (Jakob, 2005). Sediment recharge rates are dependent on sediment production and erosion rates (weathering and delivery), which are functions of lithology, climate, and basin morphology. Channels in supply-limited basins tend to be filled with coarse material and have high hydraulic conductivity, which require large amounts of precipitation and runoff to trigger a debris flow. Thus, not only is the triggering hydroclimatic threshold higher in supply-limited basins, but long time periods may be required to accumulate sufficient sediment for transport (Jakob, 2005). Once a debris flow occurs in a supply-limited basin, another debris flow cannot occur until sufficient time has passed to build up enough material for another event. If an extreme rainfall occurs before the sediment supply is available, the resulting flow may be a water flood or hyperconcentrated flow. Based on geologic mapping of debris-flow deposits observed at the base of the Santa Catalina Mountains, their recurrence intervals were estimated to be on the order of 1,000 years (Youberg and others, 2008). The frequency of debris flows in Maricopa County may be as low or lower (i.e., less frequent) due to generally drier conditions, lower elevations, sparser vegetation and shallower soils compared to the Santa Catalina Mountain area.

Prior to 2006, the trend of decreasing size and extent of debris-flow deposits from the late Pleistocene to late Holocene, along with the dearth of historical debris flows, suggested that debris flows did not represent a significant geologic hazard in Arizona (Webb and others, 2008b). That view was challenged when an unusual weather pattern in late July, 2006, resulted in approximately 1,000 hillslope failures in four mountain ranges across southeastern Arizona (Pearthree and Youberg, 2006b; Magirl and others, 2007; Webb and others, 2008b) as shown in Figure 1. Although much of the Santa Catalina mountain range had burned in 2003, nearly all of the hillslope failures initiated in areas that either had not burned or had been subject to low-severity burns (Webb and others, 2008b). Most of these hillslope failures transformed into debris flows that traveled only short distances well within the mountain front, although some coalesced into larger debris flows and traveled surprisingly far (Webb and others, 2008b). Debris flows damaged or destroyed infrastructure in Coronado National Memorial (Huachuca Mountains) and in Sabino Canyon (Santa Catalina Mountains). Debris flows exited or nearly exited the mouths of five canyons along the front range of the Santa Catalina Mountains (Figure 5), and caused significant alluvial fan flooding at the mouth of Soldier Canyon (Webb and others, 2008b).

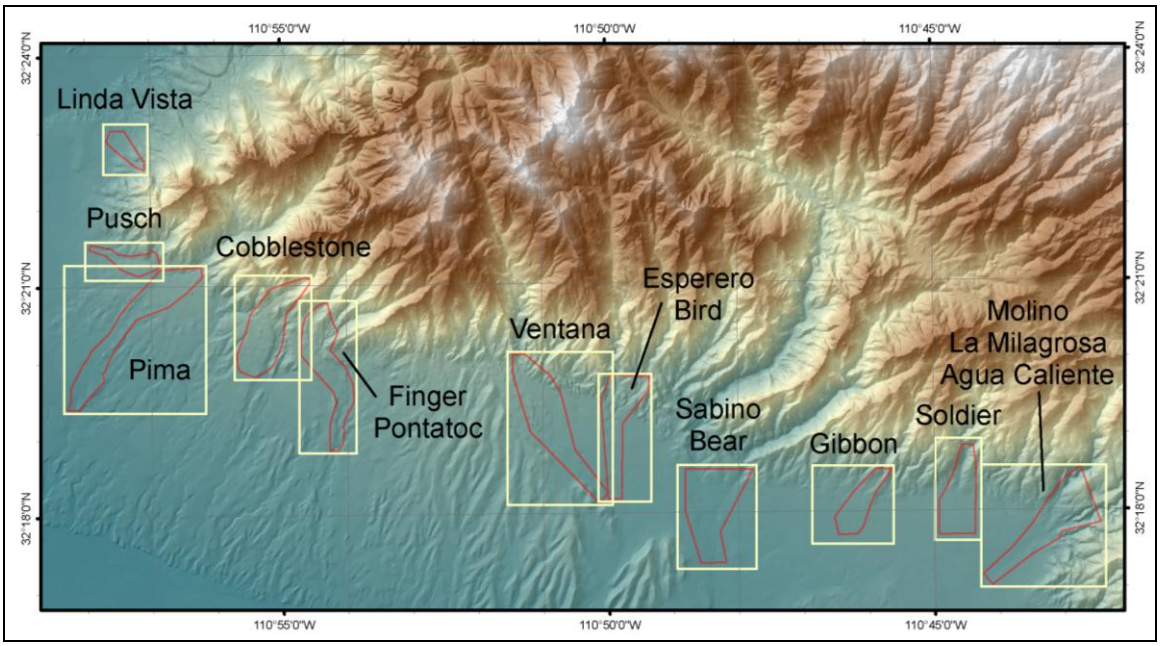

Figure 5. Alluvial fans included in the geologic mapping of paleodebris-flow deposits along the Santa Catalina front range. Debris flows exited the mountain front in Soldier and Gibbon Canyons, and almost exited the mountain front in Bear, Sabino and Bird Canyons. (Youberg and others, 2008).

The events in Soldier Canyon from the July 2006 storms illustrates the most likely (albeit highly infrequent) impacts of debris flows on alluvial fan flooding expected for the developed areas around the base of low desert mountains in Maricopa County. In Soldier Canyon, Webb and others (2008b) documented 56 hillslope failures within the watershed. These hillslope failures coalesced into debris flows and travelled down canyon onto the Soldier Canyon alluvial fan (Figure 5). Pre- and post-event orthophotographs from 2005 and 2007 show significant channel widening and sediment deposition occurred during the 2006 debris flows and floods (Figure 6). It is important to note that the active fan surface at the mouth of Soldier Canyon is adjacent to the mountain front, unlike most of the alluvial fans in Maricopa County. Sediment from at least two debris-flow pulses reached the Mt Lemmon Short Road crossing near the fan apex, plugging the bridge and channel. The recessional flood was then forced to spread out across the fan head (Figure 7) which caused extensive damage to infrastructure and one house (Youberg and others, 2008).

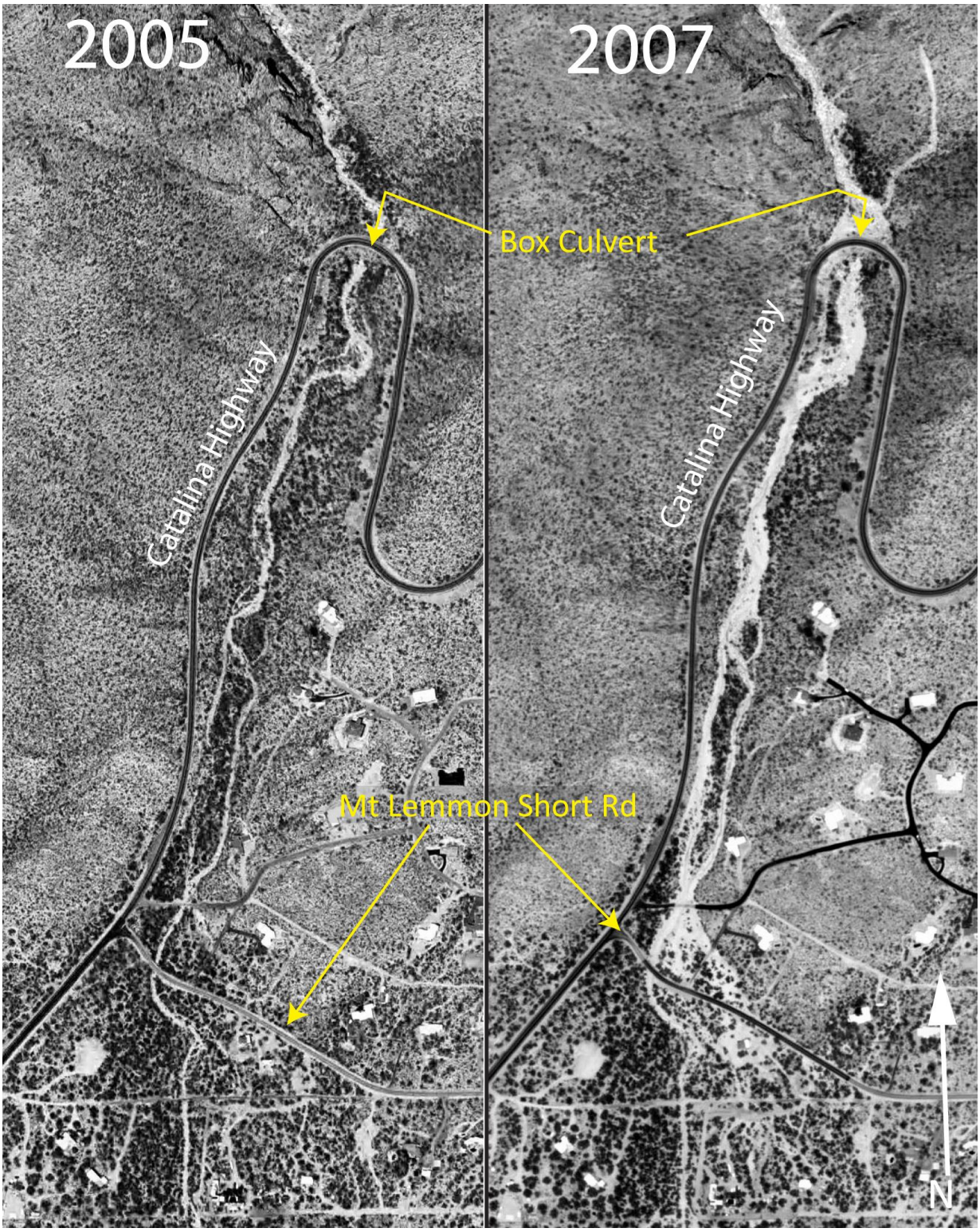

Figure 6. Comparison of Soldier Wash channel between 2005 (left) and 2007 (right). Debris flows and floods significantly widened the channel; older, abandoned channels were re-occupied. (Modified from Youberg and others, 2008).

Figure 7. Soldier Canyon fan – impacts from 2006 debris-flows. Upper left: boulder snout of debris flow upstream of the Mount Lemmon Short Road. The debris-flow deposit was deposited after, and on top of, an earlier pulse that likely plugged the bridge (Photo: P.G. Griffiths, Sept. 12, 2006). Upper right: Mt Lemmon Short Road bridge plugged by debris-flow deposits (Photo: C. S. Magirl, 9-12-06). Lower left: aerial view of debris-flow deposits (yellow lines) and recessional flood flow (blue lines) (Photo: P.G. Griffiths, 9-3-06). Lower right: view upstream of the plugged Mt Lemmon Short Road bridge (Photo: P.G. Griffiths, 9-12-06).

Debris Flow Generation in Arizona

Historical hydrological conditions that have generated debris flows in central and southern Arizona are quite varied. Debris flows have been documented following short-duration, high-intensity summer convective storms, long-duration, less-intense, regional winter frontal systems, and widespread and intense late summer to early fall dissipating tropical storms (Webb and Betancourt, 1992; Griffiths and others, 1996). In the lower desert regions of Arizona, similar to conditions in Maricopa County, debris flows have been documented from these different storm types. For example, numerous debris flows occurred in the Picacho Mountains during the incursion of tropical moisture from Tropical Storm Octave in 1983, and in 2008 debris flows occurred in the Ajo Mountains following an intense summer convective storm. Debris flows have also occurred following wildfires from high-frequency, low-magnitude monsoonal storms (Wohl and Pearthree, 1991; Pearthree and Youberg, 2004). Following the 2004 Willow

Fire near Sunflower, a 5- to 10-year frequency monsoonal storm generated debris flows in every burned drainage along State Route 87 at the Gila-Maricopa County line (Pearthree and Youberg, 2006a). Debris flows have also been generated from more rare and extreme storms, such as the 2006 debris flows in southern Arizona (Magirl and others, 2007). Griffiths and others (2009) analyzed radar and rain gage data from the Santa Catalina Mountains to estimate return intervals for this series of July 2006 storms. Estimated return intervals for individual daily storms were less than two years, while return intervals for average 2-day storms were greater than 50 years, and greater than 200 -500 years for the 4-day storm with return intervals up to greater than 1,000 years in some areas (Griffiths and others, 2009). These findings show that high antecedent soil moisture conditions prior to debris-flow initiation was a critical factor for the 2006 event (Griffiths and others, 1996; Webb and others, 2008b). Youberg and others (2008) concluded that debris-flow frequency in individual canyons in the Santa Catalina Mountains are on the order of a thousand years, somewhat longer than the most extreme return intervals estimated for the storms of 2006. The low desert mountains of Maricopa County is likely to have even lower return intervals than the higher mountain ranges in southern Arizona due to the lower elevations, slow sediment recharge rates, and low annual rainfall.

The mountains and associated alluvial fans in the developed, low desert areas of Maricopa County, have characteristics that make them less like to have debris flows that would impact alluvial fan flooding, compared to more mountainous areas of the county or the state. The low desert mountains, in general, have moderate relief, but channel gradients near the mountain fronts tend to be low, making it more difficult for debris flows to travel down channel and reach the piedmont, much less the mid-piedmont alluvial fan apexes. In addition, the hot and dry climatic conditions result in low sediment production and shallow hillslope soils, limiting available sediment. Wildfires are unlikely in this environment as the desert vegetation is typically too sparse, except in the wettest years (e.g. 2005), to carry fire. Therefore, hydrologic changes due to fire and the increased likelihood of post-fire debris flows do not typically apply to the low desert mountains of Maricopa County. Another factor influencing the likelihood of debris flows to impact alluvial fan flooding is the location of the active fan surface to the mountain front. If the active fan surface is adjacent to the mountain front then it is more likely debris flows could impact alluvial fan flooding. Many alluvial fans at the base of the low desert mountains in Maricopa County have active fan surfaces removed from the mountain front. Typically, these fans are fed by incised, low gradient, feeder channels. The distance from the mountain front and the low gradient channels make it very unlikely that debris flows will impact alluvial fan flooding in Maricopa County.

Methods for Modeling Debris-Flow Hazards

This section provides a discussion of debris-flow hazard assessment models that could be used to quantify how debris flows influence alluvial fan flood hazards in Maricopa County. In addition, some examples of debris-flow hazard assessments are presented. A comprehensive review of all available models is not presented. Rather, the models most useful for assessing potential debris-flow occurrence and runout capability in Maricopa County are reviewed. The challenge in identifying appropriate methods lies in the fact that most methods and models have been developed in wetter climates, where model testing and calibration is easier due to the higher frequency of occurrence of debris flows. Data used to test and calibrate models includes LiDAR-derived topography, extensive soils information, existing landslide inventories, detail maps of previous debris flows, and measured debris-flow parameters such as matrix composition, basal friction, flow depth and flow velocity. In the absence of these detailed data, results from debris-flow hazard models will, at best, be a preliminary assessment.

Importance of Geologic Reconnaissance Prior to Modeling

The Flood Control District of Maricopa County (FCDMC) wants to assess potential hazards associated with the impacts of debris flows on alluvial fan flooding. In order to model these hazards, it must first be determined that the basin of interest is a debris-flow producing basin, and that debris flows have actually run out onto the associated alluvial fan. This requires geologic reconnaissance to evaluate whether young debris flow deposits exist in the basin of interest, and geologic mapping to determine the downstream extent of deposits. Then, models assessing the likelihood of debris-flow occurrence (initiation) and runout capability can be used to assess the potential hazard. Initiation models provide information about slope stability in basins of concern. If no evidence of historical (i.e., less than 100 years) or geologically recent (i.e., less than 10,000 years) is found, then there is no need to apply the detailed debris flow modeling techniques described below. A method that incorporates results from geologic mapping and debris-flow modeling will provide the most robust means of assessing these geologic hazards. In addition, the data collected during the geologic reconnaissance can be used to help verify and/or calibrate the modeling results, as described below.

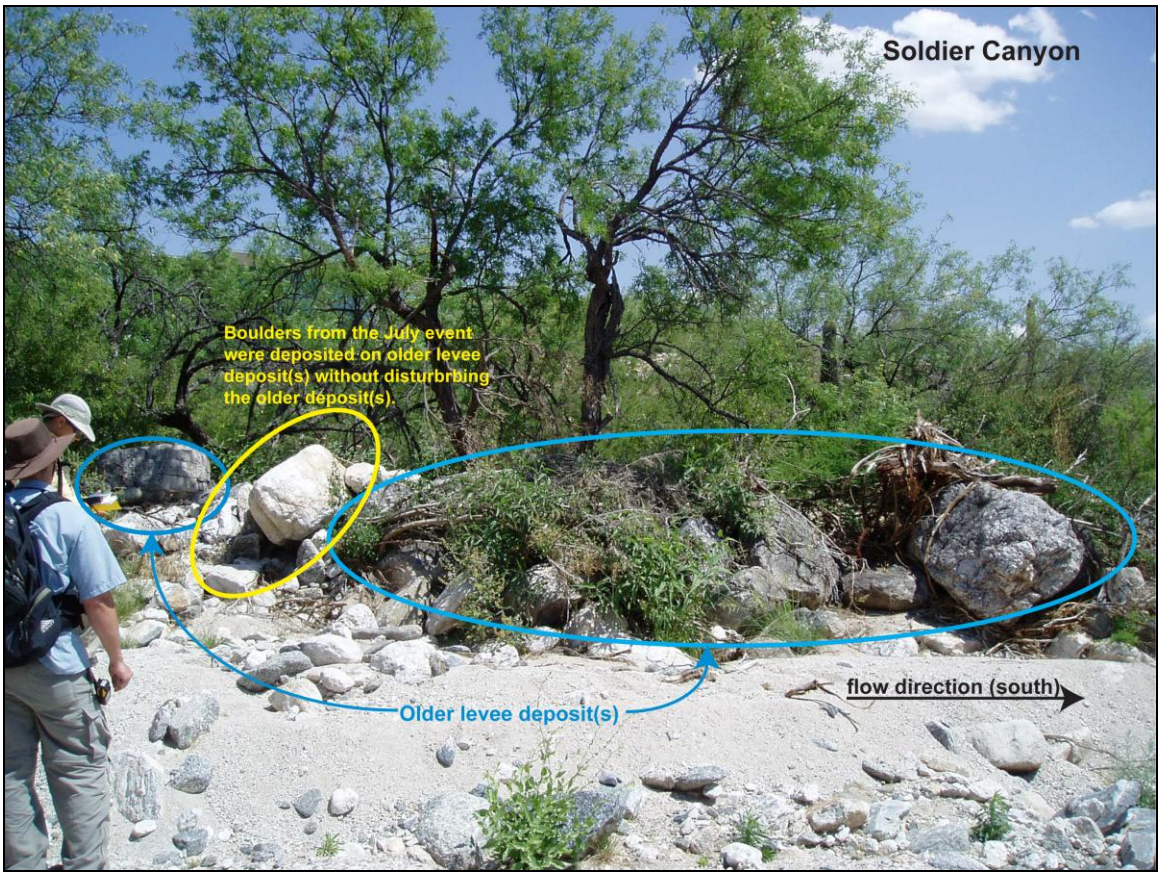

Figure 8. Examples of multiple debris-flow deposits of different ages. The fresh 2006 deposits are clearly visible now, but will be less so over time. (Modified from Youberg and others, 2008)

Recognizing Debris-Flow Prone Basins and Fans

Many factors determine whether or not debris flows can occur in a drainage basin, and how far they will travel. While models can provide information to assess the likelihood of debris-flow occurrence and runout, verification that there is physical evidence of young debris flows is a key component of any hazard assessment. Geologic reconnaissance involves field investigations to determine if deposits characteristic of debris flows are present. Key characteristics indicative of debris flows are large caliber sediment, linear arrangement of boulders along channels (levees), and bulbous, coarse boulder aggregations where debris flows stopped or changed direction (snouts). Geologic reconnaissance also includes a review of previous geologic and geotechnical reports, aerial photographs, soils data, and other historic information (e.g. newspaper articles) that may shed light on past debris flows. If young debris flow deposits exist along a channel, mapping them will provide information regarding past debris-flow travel distances, relative ages of deposits, and a minimum number of past debris-flow events (Figure 8) (Youberg and others, 2008). Although geologic data generally will not provide a complete census of individual debris flows, information regarding ages, extent and number of debris-flow deposits can provide valuable information regarding trends in debris-flow travel distance, volumes, and clast sizes.

Debris Flow Model Classification

Models have been developed to assess debris-flow behavior (Iverson and Denlinger, 2001), to estimate debris-flow erosion (Stock and Dietrich, 2006), and to predict debris-flow hazards (O'Brien and others, 1993; Wilford and others, 2004; Cannon and Gartner, 2005). There are two general classes of debris-flow models:

- Initiation models
- Runout models

Initiation models evaluate slope stability conditions to identify areas of potential slope failure and assess the likelihood of debris-flow occurrence. Runout models evaluate potential travel distance from the initiation point to the debris-flow deposition zone, which in some cases may be on alluvial fans. While initiation and runout models can provide hazard information regarding likelihood of occurrence or potential runout distances, they will not provide any information with respect to frequency-magnitude relationships. Actual occurrences and expected volumes are not predicted by these models. These models address debris flows generated from extreme precipitation, rapid snow melt, or as a result of disturbance due wildfires. Selection of a particular model depends on project goals, available data, and funding.

Debris flow models can be further classified as physically based or empirical. Physically-based models are rooted in classic physics, and incorporate mass, energy, and/or momentum conservation laws (Wilcock and others, 2003). These models can be very detailed, data intensive and expensive. Some of the more rigorous models may be best suited for post debris-flow assessments. Other physically-based models use generalized parameters and simplifying assumptions (Rickenmann, 2005). These models can provide good results but require input parameters that are difficult to estimate, such as travel velocity and friction coefficients. The models also require extensive field calibration (Fannin and Wise, 2001). Empirical models are based on field observations, measurements, and statistical relationships, and should only be used in the areas and conditions under which they were developed, or be re-calibrated using local data (Fannin and Wise, 2001).

Initiation Models

Initiation models assess slope stability conditions to identify areas of potential slope failure. Most of these models employ the same equation, but calculate the parameters and results differently. The most common models are used in a grid-based geographic information system (GIS), which partitions topography into

regularly celled digital elevation models (DEMs) and allows for rapid spatial analysis of large areas. Models that use GIS can incorporate diverse factors including topography, geology, soils, hydrology, and vegetation to evaluate slope stability and potential debris-flow initiation. Most models evaluate slope stability using the infinite slope form of the Mohr-Coulomb failure law;

$$\tau = c' + (\sigma - \mu) \tan \varphi \qquad (1)$$

where τ is the shear stress, c' is effective cohesion, σ is normal stress, μ is pore pressure, and tan Φ is the internal friction angle of the soil. The left side of this equation represents shear stress, or the driving forces, while the right side represents shear strength, or resisting forces. For slope stability analysis this equation if often rearranged to calculate the factor of safety (FS) for each DEM cell by finding the ratio of resisting forces to driving forces:

$$FS = \frac{C_r + C_s + \cos^2 \alpha [\gamma_s (D - D_w) + (\gamma_s - \gamma_w) D_w] \tan \emptyset}{\sin \alpha \ \cos \alpha \ (\gamma_s D)} \qquad (2)$$

where C_r and C_s are root strength and soil cohesion, D is the vertical depth of the soil and D_w is the vertical depth of the saturated zone, γ is the unit weight of water (w) and soil (s), and α is the slope. Slopes are considered stable when FS>1 and unstable when FS<1.

There are four commonly-used debris flow initiation models that incorporate the infinite slope equation (1) in the factor of safety form (2). All of the models are physically-based and can be used in any environment, including Maricopa County. The following models are discussed in more detail below:

- SHALSTAB
- SINMAP
- LISA
- TRM

SHALSTAB. SHALSTAB (Montgomery and Dietrich, 1994) is a steady-state model that couples a hydrologic model with gridded topographic data (Dietrich and Montgomery, 1998). SHALSTAB calculates a topographic index based on contributing area per unit contour length, which is assumed to be equal to the cell resolution of the DEM. The FS equation is re-arranged to calculate a critical rainfall rate at which the slope will fail. SHALSTAB attempts to be as parameter-free as possible and requires only a single value for each input parameter. The default version of SHALSTAB requires input describing the soil bulk density and internal friction angle (Table 1). A newer version of SHALSTAB also allows input for effective cohesion (soil + root strength) and soil depth (Witt and others, 2007; Harp and others, 2008). From these parameters SHALSTAB calculates transmissivity and effective rainfall to determine a critical steady-state rainfall rate for slope instability (Montgomery and Dietrich, 1994). Cells are then classified as unconditionally stable, stable, unstable, and unconditionally unstable. Unconditionally stable slopes are slopes that won't fail even at full saturation, and sometimes includes rock outcrops. Unconditionally unstable slopes often have internal friction angles, Φ, less than slope angles, α, and can fail with less saturation. SHALSTAB assumes steady-state hydrologic conditions, uniform soil depth, constant saturated hydraulic conductivity, subsurface flow parallel to surface topography, and neglects friction along the sides of the failure plane (Montgomery and Dietrich, 1994). Data requirements for SHALSTAB are DEMs and single values for selected soil parameters. Benefits of the SHALSTAB model are that it can be applied across diverse environments, it is less costly to parameterize, and different sites can be directly compared. However, some studies have found that the model can fail to produce results that

match on-the-ground conditions (Dietrich and Montgomery, 1998). However, a failed model can indicate that physical processes other than those being modeled are influencing slope failures, which also is valuable information.

SINMAP. SINMAP (Pack and others, 2005) is a steady-state model that follows in the footsteps of SHALSTAB, but differs in a few key ways. SINMAP uses the same FS equation (2) and makes the same assumptions as SHALSTAB: steady-state hydrologic conditions, uniform soil depth, constant saturated hydraulic conductivity, subsurface flow parallel to surface topography, and neglects friction along the sides of the failure plane. SINMAP allows the user to provide a range of values for input parameters which are then distributed using a uniform probability distribution function (Table 1). Parameters input by the SINMAP user include rainfall rate, transmissivity, cohesion, internal friction angle, and soil depth. SINMAP calculates a FS for each cell and assigns a stability index (SI) based on the FS. If $FS \geq 1$, the slopes are stable. If $FS < 1$, a stability index (SI) is calculated based on the probability of failure for the best and worst conditions for the range of soil parameters described by the uniform probability functions (Pack and others, 2005). Data requirements for SINMAP include DEMs, ranges for selected soil parameters, and rainfall rates (Table 1). An advantage of SINMAP is that a study area can be broken into homogeneous regions to reflect different localized conditions.

LISA. The Level I Stability Analysis model (LISA) developed by the US Forest Service (Hammond and others, 1992) is similar to SINMAP. LISA uses the same FS equation (2) as SINMAP, but also includes a tree surcharge factor (Table 1). LISA uses probability distribution functions defined by the user to describe all soil parameters and the rainfall distribution. The factor of safety is calculated for up to 1000 different combinations of site conditions using a Monte Carlo simulation. These distributions are shown as histograms (Hammond and others, 1992), and a failure probability is then calculated for the different combinations (Morrissey and others, 2001). Like SINMAP, LISA can divide the study region into different subareas to reflect local soils and geologic conditions. LISA model assumptions are the same as SHALSTAB and SINMAP. Data requirements include DEMs and a range of values for all soil parameter and rainfall distribution.

TRM. Iverson's (2000) transient response model (TRM), also uses the factor of safety approach with the infinite slope equation, but uses the Richard's equation (Jury and others, 1991) to calculate pore pressure response to transient rainfall of individual storms (Iverson, 2000). Pore pressures are calculated for vertical flow to find where in the soil column instability occurs. The model assumes that rainfall influences subsurface flow by modifying water table heights, subsurface flow is parallel to the surface, slopes are initially wet, and the catchment area is much greater than the depth of the landslide (Iverson, 2000). The benefit of the TRM model is that it evaluates slope stability in terms of spatial and temporal changes to pore pressure (Morrissey and others, 2001). Results from this model may be used to create hazard maps, although such maps are not automatically generated.

Table 1. Methods to model debris-flow initiation.				
Model	**Model parameters**	**User-provided data**	**Results/Products**	**Comment**
SHALSTAB	Soil bulk density, ρ_s Internal friction angle, Φ Effective precipitation, q Transmissivity, T In the newer version: Effective cohesion, c	Single values for: Soil bulk density, ρs Internal friction angle, Φ New version: Effective cohesion, c Soil depth, d	Creates a GIS-based hazard map from a calculated critical steady-state rainfall for slope stability. Cells are classified for slope stability as Unconditionally Stable, Stable, Unstable, Unconditionally Unstable	Requires verification with existing data
SINMAP	Steady-state recharge rate,R/T Effective cohesion, c Internal friction angle, Φ	Range of values for each region: Rainfall rate, R Transmissivity, T (=Kd) Hydraulic Conductivity, K Soil depth, d Soil bulk density, ρ_s Internal friction angle, Φ Effective cohesion, c	Creates a GIS-based hazard map from calculated factors of safety and a slope stability index (SI)	Requires verification with existing landslide data
Level 1 Stability Analysis, LISA	Steady-state Soil depth, moist (d_m) & saturated (d_s) Soil bulk density, moist (ρ_m) & saturated (ρ_s) Root and soil cohesion, C_r & C_s Tree surcharge, q_o Internal friction angle, Φ	Each parameter assigned constant value or user-defined probability distribution function: Soil depth, moist (d_m) & saturated (d_s) Soil bulk density, moist (ρ_m) & saturated (ρ_s) Cohesion, root (C_r) & soil (C_s) Tree surcharge, q_o Internal friction angle, Φ	FS is calculated for up to 1000 different combination of site conditions using a Monte Carlo simulation. Probability of failure then calculated.	Can generate hazard maps based on probability of failure for different regions.
Iverson's transient response model (TRM)	Pore pressure head, P; in the vertical direction, Z Time, t	Catchment area, A Landslide thickness, H Hydraulic diffusivity, D_o Rainfall duration, T Initial steady state water table depth, d Infiltration rate (equal to rainfall rate), I Hydraulic conductivity, k Friction angle, soil (ϕ) and slope (α) Soil cohesion, c Soil bulk density, ρ_s	Factor of safety is calculated by balancing gravitational stresses, basal frictional stress, and pore pressure.	Evaluates timing and location of landslides using pore pressure and an FS approach.

Discussion. Several comparisons have been made for some of these models. Morrissey and others (2001) compared results from SINMAP, LISA, and TRM for slope stability using data from Madison County, Virginia, where over 600 debris flows were triggered during a June 27, 1995, rainstorm. All three models produced similar soil and hydrologic property results (Morrissey and others, 2001). Only SINMAP

provided a hazard potential map that could be directly compared to a previously existing landslide hazard map. However, SINMAP over-predicted the hazards due to some inherent assumptions in the model, such as uniform soil depth and landslide thickness (Morrissey and others, 2001). The authors found that while LISA and SINMAP calculated failure probabilities by similar methods. LISA was preferred over SINMAP because all soil parameters and rainfall rates could be described by probability distribution functions which they felt caught the heterogeneous soil conditions better and increased the accuracy of prediction (Morrissey and others, 2001). The overall preferred model was Iverson's TRM because slope stability was analyzed according to spatial and temporal changes in pore pressure in response to individual storms (Morrissey and others, 2001).

Witt and others (2007) compared SINMAP and SHALSTAB to determine which model to use for their debris-flow hazard mapping in North Carolina. They found both methods made similar predictions, but chose SINMAP for its factor of safety classifications of slope stability, as they felt planners, engineers and the public would better understand the model results (R. Wooten, written communication, 2009).

Meisina and others (2007) compared SINMAP and SHALSTAB for shallow colluvial landslides in Italy. They found SHALSTAB worked well for the study area with non-extreme events but overall preferred SINMAP due to its flexibility in determining soil and rainfall values. Note that all of these studies had landslide inventories and data from recent extreme events to which to calibrate their models. All of the authors noted how important calibration data sets were for extracting realistic model results.

Runout Models

Runout models evaluate the potential travel distance of debris flows away from the initiation and transport zone into the deposition zone. Several factors influence runout distances, including flow composition and rheology, flow volume, channel slope, channel angles, loss of confinement, and obstructions, as shown in Table 2 (Benda and Cundy, 1990; Fannin and Wise, 2001; Rickenmann, 2005). Some runout models predict total travel distance while others predict runout distance, which is the length traveled just in the deposition zone (Rickenmann, 2005). Runout prediction models can be dynamic or empirical. Dynamic models are physically based and typically require parameters such as flow velocity and friction coefficients, which can be very difficult to determine. Sometimes these parameters are selected using simplifying assumptions, calibration, and/or back calculation (Fannin and Wise, 2001). Many dynamic debris-flow runout models are based on avalanche runout models (Rickenmann, 2005). Empirical models predict runout distances based on a set of statistical relationships developed from observed data, without considering the physics or mechanics controlling the flow and deposition (Fannin and Wise, 2001). The main limitation of empirical models is that they should only be applied for the conditions under which they were developed, or re-calibrated for local conditions. If used properly, empirical models provide very practical methods for hazard assessments.

Models have also been developed to estimate runout length in the depositional zone. Although hazards from a debris flow occur all along the flow path, runout within the deposition zone will have greater impact on alluvial fan flooding. In addition, long runout distances may be required to extend beyond the mountain front and reach the apexes of mid-piedmont alluvial fans. Some methods for modeling runout distance in the deposition zone include:

- LAHARZ
- FLO-2D

Both LAHARZ and FLO-2D were developed with data from outside Arizona. However, LAHARZ has been calibrated and used to model runout distances in southeastern Arizona. FLO-2D was initially based

on work done in Colorado but has been applied to numerous settings throughout the western US (Fuller, 2008; 2009) and the world (Hübl and Steinwendtner, 2001; Garcia and others, 2003; Sosio and others, 2007; Armento and others, 2008). FLO-2D is a dynamic model and LAHARZ is an empirical model. Other available dynamic models either require detailed data from historical debris flows, such as debris-flow basal friction, flow velocity and flow thickness,[3] or were developed for experimental and research purposes (for example Iverson and Denlinger, 2001). While any chosen empirical model will require calibration for use in Maricopa County, the models described below are most appropriate for the types of data available.

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Table 2.
Influence of debris-flow and environmental parameters on debris-flow runout distances

Parameter	Influence on runout distances	Likely conditions in Maricopa County
Flow composition and rheology	Granular flows with low clay content and coarse clasts have thicker deposits and shorter runout distances as opposed to fluid flows with high clay content.	Granular flows
Flow volume	Determined by available sediment supply. Function of lithology, current climatic conditions and time since last debris flow.	Flow volume is likely to be low for most watersheds, particularly those in metropolitan Phoenix.
Channel slope	Higher channel angles (~>10°) facilitate flows, while low angles (~<4°) facilitates deposition.	Alluvial fans beyond the mountain front have low slope angles, thus deposition will be above or close to the mountain front.
Channel angles	Steep channel angles (~>70°) facilitate deposition.	Site specific; influenced by factors listed above.
Confinement	Confinement facilitates flow, loss of confinement typically results in deposition.	On alluvial fans, incised channels will facilitate flow. Non-incised surfaces will facilitate deposition.
Obstructions	Obstructions can include vegetation, buildings and infrastructure (culverts or bridges). Obstructions facilitate deposition of flow.	On developed active alluvial fans, bridges and culverts will be cause for concern.

LAHARZ. LAHARZ (Schilling and Iverson, 1997; Iverson and others, 1998; Griswold and Iverson, 2008) is an empirical area-volume model. It is a GIS-based runout prediction model originally developed for volcanic-related debris flows (lahars) and recently revised to predict runout distances for non-volcanic debris flows and rock avalanches (Griswold and Iverson, 2008). It uses an empirical approach based on observations that the debris-flow inundation area (units - L^2) is proportional to flow volume (units - L^3) raised to the 2/3 power (Schilling and Iverson, 1997). This model assumes the total planimetric area, B, and maximum valley cross-section area, A, inundated by a passing flow is a function of flow volume, V, and topography (Griswold and Iverson, 2008). The LAHARZ equations are:

$$A = c_1 V^{2/3} \quad (3)$$

[3] It is unlikely that such data exist for debris flows in Arizona.

$$B = c_2 V^{2/3} \quad (4)$$

where c_1 and c_2 are coefficients determined by empirical data. The model calculates planimetric area based on user-defined volumes. Then, for each thalweg stream cell, LAHARZ calculates A and fills the valley cross-sectional area using topography until A is satisfied (Figure 9). It is important to understand that LAHARZ is modeling inundation of the largest passing snout, which is typically higher in elevation than the subsequent debris-flow deposits. The cells that form the lateral extent of A at the top of the cross-section is then applied as an increment to the total planimetric inundation area, B, and the model moves to the next downstream cell. These steps continue until B has been satisfied. The extent of B then defines the hazard zone for the given debris-flow volume.

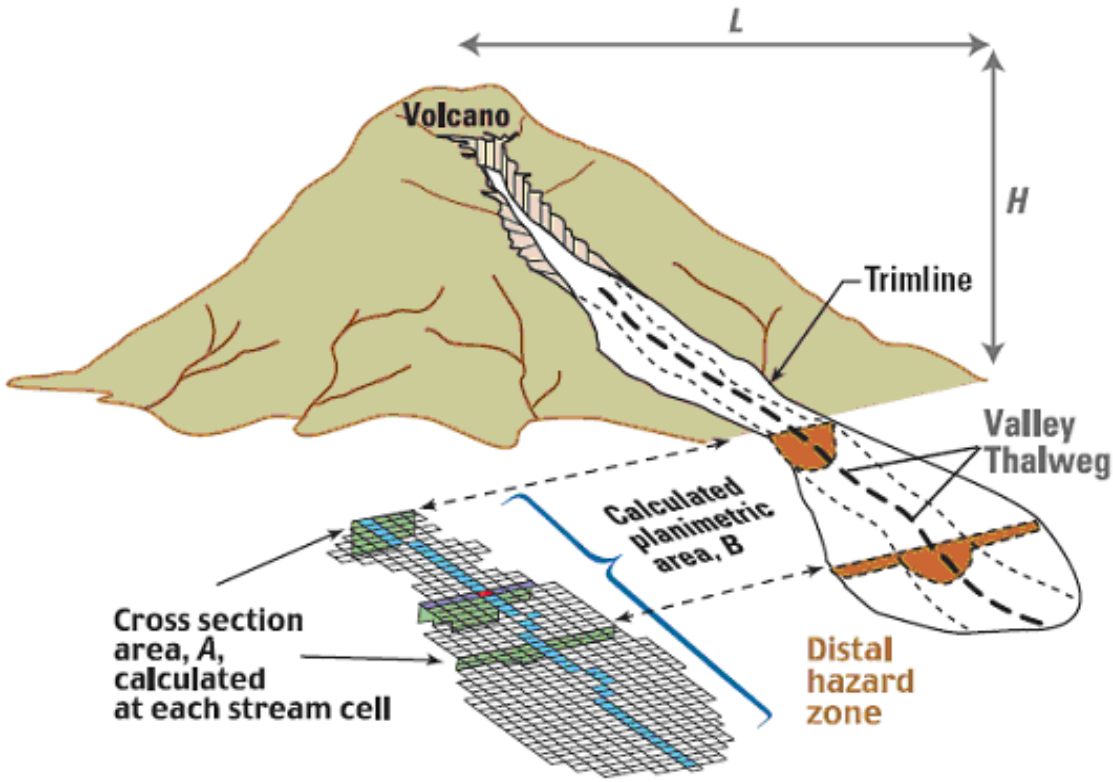

Figure 9. Diagram showing the relationship between maximum cross-sectional area, A, and total planimetric area, B. For lahars the beginning of deposition is calculated using an energy cone using a ratio of vertical decent, H, to lateral runout distance, L. For alluvial fans, the fan apex, or the fan intersection with the feeder channel will be the beginning of deposition. (Figure from Griswold and Iverson, 2008, used with permission.)

LAHARZ can calculate debris-flow hazard zones in two ways. One way is to use the "lahar" function to delineate hazard zones on the alluvial fan. The other way uses the "debris flow" function to model debris-flow travel distances within the basin to determine the likelihood of debris flows reaching an alluvial fan. The first method is based on modeling lahars. The point of beginning deposition is found using an energy cone, which is the ratio of vertical decent, H, to lateral runout distance, L (Iverson and others, 1998). To model inundation on alluvial fans, instead of using an energy cone, the fan apex or the intersection of the feeder channel with the active fan surface is selected as the point of beginning deposition. LAHARZ then calculates inundation hazard zones for user-defined volumes.

The second method uses the debris-flow function which begins deposition below potential initiation points based on a grid developed from user-defined criteria. These criteria may include parameters such as contributing area, slope, and channel gradient. For example, the user can create a grid by defining a minimum upstream contributing area, minimum slope of the contributing area, and channel gradient at which deposition begins. This grid defines the start of deposition and LAHARZ then models debris-flow travel distances downstream for a given set of flow volumes. This second method is useful for determining if debris flows that originate in a basin can travel the distance necessary to exit the mountain front and impact an alluvial fan.

Data requirements for the LAHARZ model include detailed topographic information of the deposition zone in the form of a DEM, the point where deposition begins, and a series of selected volumes to model (Table 3). Volumes are used in an iterative process to calculate potential inundation limits (Iverson and others, 1998; Griswold and Iverson, 2008). A potential problem with this model is selecting realistic debris-flow volumes. This model does provide flexibility for evaluating debris-flow travel distances and inundation. LAHARZ was tested in southern Arizona using local data to model the 2006 Santa Catalina Mountains debris flows with reasonable success (Webb and others, 2008b). The model could be further refined for locations in Maricopa County using additional modeling of historical debris flows.

FLO-2D. FLO-2D is a continuum based dynamic model that assumes Bingham or viscoplastic fluid flow. It is a grid-based, volume conservation, two-dimensional flow routing model developed to model floods and mudflows (fluid-flows) over unconfined surfaces such as alluvial fans (O'Brien and others, 1993). FLO-2D uses a full dynamic-wave momentum equation and a finite-difference routing scheme (O'Brien and others, 1993). It requires either determination of friction parameters, or needs to be calibrated to previous flow events prior to use for prediction of runout lengths (Rickenmann, 2005). Total friction is determined from three terms: yield strength, viscosity, and collision-turbulent friction. The collision-turbulent friction term dominates the faster, channelized flow whereas yield strength dominates flow stoppage (Rickenmann, 2005). FLO-2D data input requirements include detailed topography, flow roughness variables, rainfall, runoff and infiltration rates, and data regarding obstructions such as buildings and infrastructure (Table 3) (O'Brien and others, 1993; Hübl and Steinwendtner, 2001).

FLO-2D has been used to model distributary flow and alluvial fan flooding in Maricopa County and elsewhere in Arizona (JE Fuller, 2008; 2009). The model has a sediment concentration component that is used to calculate yield stresses, viscosity, and granular dispersive stresses for simulating debris-flow behavior and runout. Results from the FLO-2D model have been compared to other model results and actual flows in several studies. FLO-2D was found to model floods well, and was able to identify hazard zones relatively well for single-phased flows (Garcia and others, 2003; Armento and others, 2008). FLO-2D did not perform as well when modeling debris-flow behavior and runout distances for two-phased, coarse-grained granular flows (Sosio and others, 2007) similar to those more likely to occur in Maricopa County.

Sosio and others (2007) reconstruct debris-flow runout from the November 2002 Rossiga debris flow in the central Italian Alps to test FLO-2D's assumption that modeling that the fine-grained matrix and pore-pressure dominates flow behavior and runout distances, and that frictional and collisional effects from coarse clasts are negligible. They used laboratory tests and field data to find the grain-size distribution and rheologic properties of the flow. Based on samples from two different surge deposits, the debris flow contained 5-15% clay and had a coarse fraction with up to 50% larger than 0.5-meter clasts (Sosio and others, 2007). These researchers tested FLO-2D by using rheologic data from the Rossiga debris flow and the FLO-2D code to model runout distances. They then compared modeled distances with actual distances. They found that FLO-2D was not able to accurately predict the extent of the granular debris

flow, and that FLO-2D over-predicted the runout length due to the assumption of a smaller yield strength found in fluid flows (Sosio and others, 2007).

Other Models. Other variations on travel distance models include empirical equations based on travel angle and volume (Corominas, 1996; Rickenmann, 2005; Prochaska and others, 2008), volume-balanced approaches that model entrainment and deposition throughout the debris-flow zone (Cannon, 1993; Fannin and Wise, 2001), and mass point dynamic models based on the Voellmy two-parameter snow avalanche model using turbulence and friction components to model travel distance. These models were developed with data from Europe and California, require parameters that difficult to ascertain, and require re-calibration with data from field-documented debris flows in the region of interest. Therefore, these other models are not recommended for application in Maricopa County.

Table 3.
Methods to model debris-flow runout.

Model	Model parameters	User-provided data	Results/Products	Comment
LAHARZ	Cross-sectional area, A Planimetric area, B	GIS (GRID), topography (DEM), location of start of deposition zone, potential flow volumes.	GIS-based maps show potential extent of inundation for a series of volumes	Tested on some 2006 debris flows with coefficients derived from local data.
FLO-2D	Friction parameters: yield strength, viscosity, and collision-turbulent friction, or calibration from other events.	topography (DEM), flow roughness variables, rainfall, runoff and infiltration rates, infrastructure and obstruction data	Flow distribution hazard maps.	Modified Bingham flow with a friction parameter to account for channel roughness and turbulence.

Reconnaissance-Level Assessment of Debris Flow Potential

Several studies have developed methods to evaluate the influence of basin morphometric parameters on debris-flow initiation (Montgomery and Dietrich, 1994; Griffiths and others, 1996), transport and erosion (Wilford and others, 2004; Stock and Dietrich, 2006), and deposition zones (Benda and Cundy, 1990). Basin morphometric parameters include basin contributing area, relief, hillslope processes, geology, and climate (Tucker and Bras, 1998). Basins with higher relief and thus higher-gradient streams have greater capacity to adjust to changes in sediment supply and can transport larger clasts than smaller or low-relief basins (Montgomery and Buffington, 1997). Unfortunately, most methods using basin and channel morphometry to assess debris-flow hazards were developed in areas with different climates from Arizona. For example, Wilford and others (2004) used morphometrics to discriminate basins prone to debris-flow from flood-flow in western Canada. They found that watershed length, in combination with the Melton Ratio, a measure of basin ruggedness, was the best potential indicator of debris-flow prone basins (Wilford and others, 2004). Benda and Cundy (1990) used channel gradient and angle to determine debris-flow deposition zones in debris-flow producing basins of the Pacific Northwest. These researchers found channels gradients less the 3.5° and channel angles greater than 70° produced debris-flow deposition (Benda and Cundy, 1990). Griffiths and others (1996) found drainage-basin area, channel gradient, and river corridor aspect to be significant variables in determining debris-flow frequency in Grand Canyon. They postulate that this relationship is ties to storm tracks moving through the Grand Canyon (Griffiths and others, 1996).

Youberg and others (2008) derived morphometric data for debris-flow producing canyons in the Santa Catalina Mountains near Tucson, and found basin morphometric data useful for assessing the influence of basin size and channel gradient on debris-flow conveyance and potential deposition zones along the front

range. Their analysis indicated that larger canyons with lower channel gradients (<10%) had tributary debris flows that terminated in the main channel at the base of the hillslopes. In contrast, smaller, steeper basins had debris flows that exited or nearly exited the mountain front (Youberg and others, 2008). These studies provide some intriguing ideas for identifying debris-flow prone basins and potential deposition zones that might be applicable in Maricopa County, but would require a database of debris flow measurements from which to calibrate predictive morphometric characteristics. To date, no such database exists.

Examples of Debris-Flow Assessments

The following examples illustrate how some assessment methods have been used to evaluate debris-flow hazards.

- The Oregon Department of Geology and Mineral Industries produced 1:100,000-scale debris flow hazard maps using three models (Hofmeister and others, 2002). A GIS-analysis of slope steepness was conducted as a proxy for initiation (model #1). Debris flows were then routed through the transport zone using rules-based routing on channel gradients and topographic confinement (model #2). LAHARZ was then used to model for runout and deposition (Hofmeister and others, 2002). Oregon already had a landslide inventory completed with which to compare the model results. They also did extensive field checking, and model calibration and validation prior to finalizing their assessment.

- The North Carolina Geological Survey conducted a pilot study to develop a method for assessing landslide hazards in Macon County. This work was in response to numerous landslides generated from intense precipitation during Hurricanes Frances and Ivan (Wooten and others, 2007; Wooten and others, 2008). As part of the pilot study, they compared SINMAP and SHALSTAB. Model requirements included the ability to deal with complex terrain, geology and soils, interface with a GIS, and be easily understood by the policy makers and community while standing up to scientific scrutiny (Witt and others, 2007). SINMAP was chosen because of its factor-of-safety approach. LiDAR data, an existing landslide inventory, and intensive field mapping were used to develop the methodology, test the models and create hazard maps.

- Gomes and others (2008) used SHALSTAB, in conjunction with a deposition prediction model based on channel gradient and channel angle (Benda and Cundy, 1990), to model debris-flow hazard zones in Brazil. They used an iterative GIS approach to the model deposition zones, and compared model results to mapped debris flows that occurred during intense summer rainfall in 1996. Results matched well to actual data (Gomes and others, 2008).

These few examples show how combining different models can be an effective approach to assessing debris-flow hazards, if field observations or historical records of past debris flows are available.

Debris Flow Impacts on Alluvial Fans in Maricopa County

There is ample evidence that debris flows have occurred in Maricopa County in the past. For example, (Péwé, 1978) describes minor debris flows that occurred in steep mountainous areas located within the City of Phoenix during the mid-1970's. There are, however, no documented cases of historical debris flows traveling onto active, mid-piedmont alluvial fans that affecting flooding or flood hazards. This was also true in Pima County until 2006, when debris flows traveled onto the Soldier Canyon alluvial fan and impacted some roadway infrastructure and altered ground elevations in the floodplain. Based on known characteristics of debris-flow behavior in general, and the specific climatic and geologic conditions in

Maricopa County, debris flows are expected to have low-frequencies and long recurrence intervals (> 1000 years; Webb and others, 2008b; Youberg and others, 2008). Modern debris flows probably will have low volumes, because of the limited sediment supply in the watershed, and short travel (runout) distances due to coarse composition and low clay content. Therefore, most debris flows are highly unlikely to reach the active areas of alluvial fans, particularly those fans that are located away from the mountain front. While the occurrence of debris flows is relatively rare, the impacts from those that do travel to alluvial fans could be significant. Models, in conjunction with geologic reconnaissance and mapping provide a method with which to evaluate debris-flow potential to impact fan flooding, as described below.

Recommendation Debris Flow Modeling Approach

This study evaluated methods to quantify the risk of debris-flow initiation and runout potential to impact alluvial fan flooding hazards in Maricopa County. Based on the District's goal of assessing debris-flow potential to impact alluvial fan flooding, the following steps are recommended:

- Initial Assessment of Alluvial Fan
- Geologic Reconnaissance
- Debris-Flow Runout Hazard Modeling

The first step in the recommended approach is to select a fan of interest and determine if the alluvial fan is adjacent to or distant from the mountain front. If the alluvial fan is distant from the mountain front, it is highly unlikely debris flows will impact alluvial fan flooding and there is no need to proceed with further assessment of debris flow impacts. If the alluvial fan is adjacent to the mountain front, then the next step is a geologic reconnaissance to determine if debris flows have occurred in the basin of interest, and if any debris flow deposits are found on the fan.

Geologic reconnaissance of the watershed and alluvial fan, especially near the fan apex, will confirm the presence or absence of debris-flow deposits, and provide details of the basin and piedmont conditions that will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. If debris-flow deposits are not found in the watershed or on the alluvial fan, it is not a debris-flow producing basin and no further debris flow hazard evaluation is warranted. If debris-flow deposits are in found in the basin and/or on the fan then the deposits should be geologically mapped. Detailed field mapping of young debris flow deposits at and below canyon mouths can provide real data to help constrain estimates of debris flow volumes and runout distances using the procedures outlined in Youberg and others (2008). This field-mapping step is critical to realistically assess the potential impacts of debris flows on alluvial fan flooding under modern climate conditions. If debris-flow deposits are found on the alluvial fan then additional modeling will be required to assess the potential impacts to alluvial fan flooding hazards.

The next step is to model various debris-flow volumes using LAHARZ as shown in Chart 1. The first phase of the recommended LAHARZ methodology uses the lahar function, where deposition zone begins at the apex of the active fan area. Various flow volumes should be modeled, in ½ order of magnitude increments, to estimate potential volumes required to emplace debris-flow deposits at the farthest distance the youngest deposits (late Holocene to modern) were mapped. Debris-flow maps will provide the basis for determining potential deposition zones and modeling flow volumes. Results from LAHARZ can also then be used to identify potential hazard zones on alluvial fans.

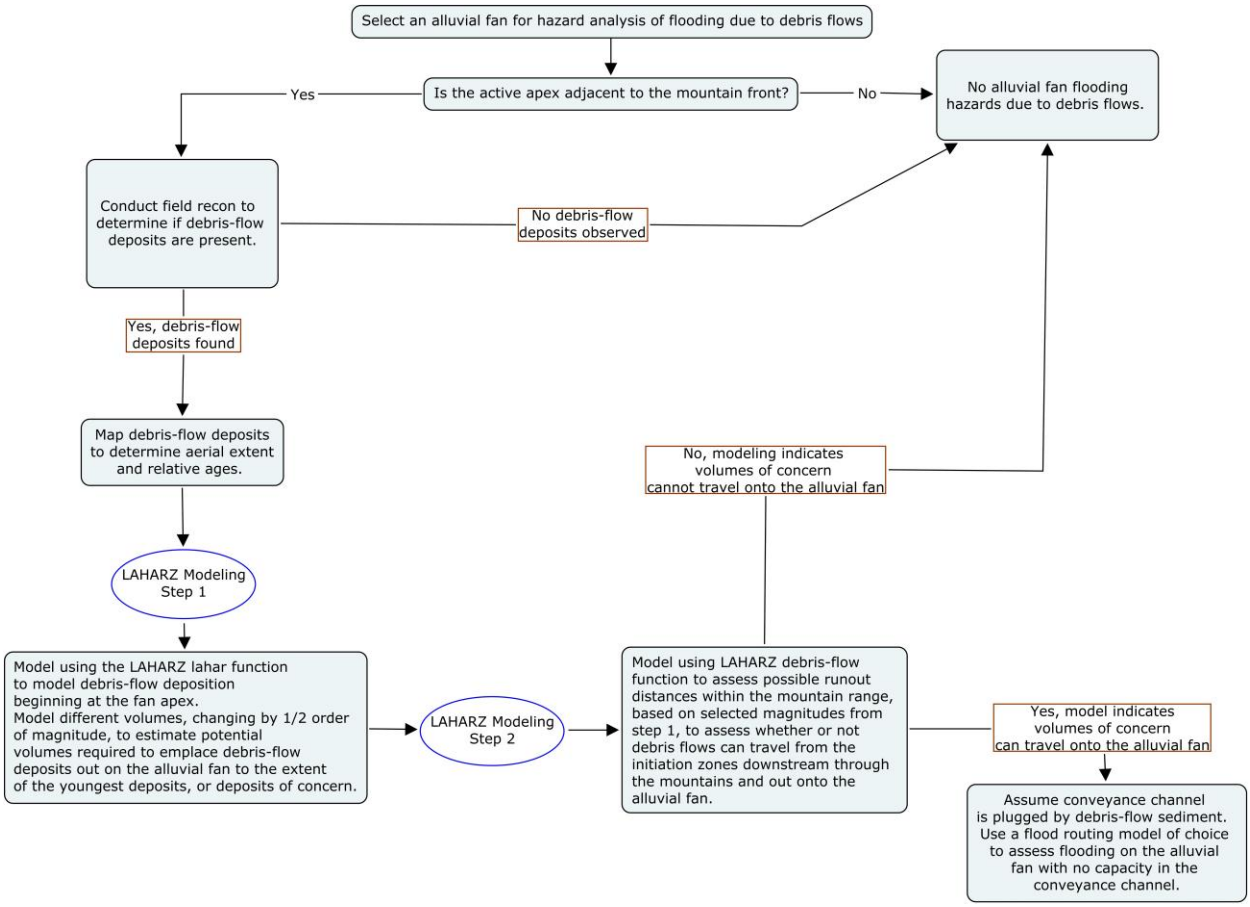

Chart 1. Flow chart showing recommended steps to evaluate the potential for debris flows to impact alluvial fan flooding.

Once potential volumes have been estimated, a geologic analysis of material available is required. For example, if the model indicates 100,000 cubic yards of material are required to emplace debris-flow deposits on the fan, then that volume can be compared to the average depths of hillslope soils, as well as to the material volume stored in upstream channels. The sediment production rate should also be compared to the required volume to determine if the basin can produce enough material to reach the modeled volumes. If sufficient sediment material is available, then the second phase of LAHARZ modeling should be conducted using the debris flow function.

The purpose of the second phase of LAHARZ modeling is to determine if debris flows produced in the basin can actually travel to the alluvial fan. Deposition zones for this phase will be based on field- and GIS-derived data, such as minimum contributing area and slopes, channel gradients, and soils data if available. The second phase of modeling will take several iterations, as the modeler will need to consider the effects of coalescing debris flows. If the modeling indicates that debris flows cannot reach the alluvial fan, then it is unlikely that debris flows will impact alluvial fan flooding. If the modeling indicates that debris flows can reach the fan, then the assumption that the conveyance channel can become blocked with sediment should be made, at which point more traditional distributary alluvial fan flooding models (e.g., FLO-2D) can be applied. The greatest impact debris flows may have on flooding is to block existing channels with sediment, forcing the following floods onto other areas on alluvial fans.

Model Testing, Validation and Calibration

Application of debris-flow runout models like LAHARZ will provide hazard information regarding potential travel distances, as well as the volumes required to reach those distances. It should be noted that these methods will not provide any information to quantify frequency-magnitude relationships or the actual risk of debris-flow occurrence or expected volumes. Initiation modeling to evaluate the likelihood of debris-flow occurrence would require significant resources in terms of time commitments to set up and run the models, and collect field data with which to calibrate the models. In addition, these models need debris flow inventories for calibrating model results. Because no such inventory currently exists for Maricopa County, one would have to be developed by qualified personnel. Without such an inventory, initiation modeling is not recommended.

Model results from LAHARZ should be locally validated and calibrated with debris-flow data from Maricopa County. LAHARZ has been calibrated using the limited data set from southeast Arizona to model the 2006 debris flows in the Santa Catalina Mountains with reasonable success. It may be possible to test LAHARZ in Maricopa County on alluvial fans with young debris-flow deposits by making generalized assumptions regarding location of debris-flow initiation, and volume estimates. The 2006 southern Arizona debris flows may act as a proxy for initiation locations and volumes. If results from these tests are satisfactory, LAHARZ can be considered ready to use in Maricopa County. Otherwise, additional calibration LAHARZ coefficients will have to be developed from newer debris flows as they occur, or other modern debris flows in Arizona that have not yet been studied in detail.

Conclusions

This study evaluated methods to quantify the risk of debris-flow initiation and runout potential to impact alluvial fan flooding hazards in Maricopa County. While there is some evidence that debris flows have occurred in Maricopa County on very steep slopes of mountainous watersheds, there are no documented cases of historic debris flows impacting flood hazards on mid-piedmont alluvial fans. Based on known general characteristics of debris-flow behavior, as well as on the specific climatic and geologic conditions in Maricopa County, the expected recurrence interval for debris flows in Maricopa County probably exceeds 1,000 years. Furthermore, because of the regional physiography and watershed characteristics, it is likely that future debris flows will have low volumes because of limited sediment supplies, will travel only short distances from their point of initiation due to their coarse sediment composition and low clay content, and that most will not reach the active areas of alluvial fans, particularly the fans that are located away from the mountain front.

To assess potential debris flow impacts on alluvial fan flooding, a combined approach of geologic reconnaissance and mapping, with a two-phase application of the LAHARZ debris-flow runout hazard model is recommended. Geologic reconnaissance will confirm the presence or absence of relatively young debris-flow deposits, and provide details of the basin and piedmont conditions which will be useful for calculating and evaluating potential debris-flow volumes. Geologic mapping will provide data regarding minimum number of deposits, relative ages, and travel distances of past debris flows. Debris-flow runout models will provide hazard information regarding potential travel distances, and the volumes required to reach those distances.

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